

Constraint on axion-like particles from atomic physics

S. G. Karshenboim*

*Pulkovo Observatory, St.Petersburg, 196140, Russia and
Max-Planck-Institut für Quantenoptik, Garching, 85748, Germany*

V.V. Flambaum

School of Physics, University of New South Wales, Sydney 2052, Australia

A possibility to constrain axion-like particles from precision atomic physics is considered.

PACS numbers: 12.20.-m, 31.30.J-, 32.10.Fn

A possible solution of the strong CP problem led to introduction of a light pseudoscalar particle called axion [1–5]. Stable or nearly stable pseudoscalar particles may also be a part of the dark matter. This has motivated an extensive search for such particles coming from cosmic space and Sun, also a laboratory search for a new spin-dependent long-range interaction which may be mediated by these particles. The limits on the interaction constants and masses of such particles as well as numerous references are presented, e.g., in the Particle Data Group issues [6].

The aim of this note is to study a possibility to constrain axion-like particles from precision atomic physics in a way similar to constraints on pseudovector particles in [7–9].

Being extracted from the measurements of muonium, hydrogen and deuterium hyperfine structure, that could produce limits on the axion-like particles complementary to macroscopic and astrophysical searches as well as to particle-physics experiments.

To avoid any model dependence, in the results presented below we do not assume any relations between the interaction strength and mass of the intermediate pseudoscalar particles which have been used to obtain the limits on the axion models presented in [6]. We also do not assume that the particles are stable or long-lived (this is assumed in the astrophysical constraints). All what we need is that their width is smaller than their mass.

Recently light pseudovector particles were constrained by studies of hyperfine structure of light atoms. A comparison of precision experimental data and an advanced theory allows to produce efficient constraint on a pseudovector particle with mass below 1 keV/c² [7–9].

Some of those constraints are summarized in Table I. The constraint comes from a study of a small exotic Yukawa-type contribution of interaction of the electron and nuclear spins

$$\frac{\alpha''(\mathbf{s}_e \cdot \mathbf{s}_X)e^{-\lambda r}}{r} \quad (1)$$

where relativistic units in which $\hbar = c = 1$ are applied.

Atom	X	$ \alpha''_0 $
Mu	$\bar{\mu}$	7.6×10^{-16}
H	p	1.6×10^{-15}
D	d	8×10^{-15}

TABLE I: The constraint from the 1s HFS intervals on a coupling constant α'' for a pseudovector boson [7, 8]. The results presented are for limit on the absolute values of the constant at the one-sigma confidence level for the limit of small masses ($\lambda \ll \alpha m_e \simeq 3.7$ keV), which is related to the Yukawa radius substantially above the Bohr radius a_0 .

As it was pointed out by P. Fayet [10], in reality an exchange by a pseudovector particle will include not only an Yukawa-type potential (1), but also a contact term. The latter was addressed in [9].

Similar contributions can also come from an axion exchange. They are studied in this paper.

The constraint on axion-mediated spin-spin coupling is

$$\tilde{\alpha}_{AeX} = \frac{\alpha''_0(eX)}{\mathcal{F}_A(\lambda/\alpha m_e)}, \quad (2)$$

where the limits on $\alpha''_0(eX)$ are presented in Table I.

The profile function \mathcal{F}_A is

$$\mathcal{F}_A(x) = -\frac{1}{3}\mathcal{F}_1(x) + 2\mathcal{F}_\delta(x), \quad (3)$$

where [8]

$$\mathcal{F}_1(x) = \left(\frac{2}{2+x}\right)^2 \quad (4)$$

and

$$\mathcal{F}_\delta(x) = \frac{4}{3x^2}. \quad (5)$$

The first term comes from the Yukawa-type interaction and the second is from the contact term (cf. [9]).

We note, that for $\lambda \ll \alpha m_e$, which means $x \ll 1$

$$\begin{aligned} \mathcal{F}_1(x) &\simeq 1 \\ \mathcal{F}_\delta(\lambda/\alpha m_e) &\gg 1, \end{aligned} \quad (6)$$

*Electronic address: savely.karshenboim@mpq.mpg.de

and finally we find for small λ

$$\tilde{\alpha}_{AeX} = \frac{3}{8} \alpha_0''(eX) \frac{\lambda^2}{(\alpha m_e)^2}, \quad (7)$$

The most strong constraint can be set on $e\mu$ coupling via an exchange by an axion-like particle. Combining the experimental result [11] on the $1s$ hyperfine interval in muonium with theory [12] (see also [8, 13] for details and references) we find (cf. [7, 8])

$$|\tilde{\alpha}_{Ae\mu}| \leq (2.8 \times 10^{-16}) \frac{\lambda^2}{(3.7 \text{ keV})^2}. \quad (8)$$

Similar but weaker constraints can be set on the ep and en coupling (cf. [8, 9]). For the latter we take into account that in deuterium

$$s_n \simeq \frac{1}{2} s_d.$$

We also note that the deuterium constraint is substantially weaker than that for hydrogen, which allows to neglect the proton contribution and thus we obtain for the effective ed coupling

$$\tilde{\alpha}_{Aen} = 2\tilde{\alpha}_{Aed}. \quad (9)$$

It is useful to express the effective coupling constant due to exchange by an axion-like particle in more fundamental terms, i.e. in terms of a vertex of emission of such a particle by a fermion, which may be parameterize as

$$x_i \frac{m_i}{v} A \langle \Psi_i | \gamma_5 | \Psi_i \rangle, \quad (10)$$

where $i = e, \mu, p, n$, while A stands for the axion-like field. Here, v is the vacuum average of the Higgs field from the

standard electroweak theory

$$v = 246 \text{ GeV}$$

and x_i are the parameters to constrain.

Combining the parametrization (10) with Eq. (6) we find

$$\begin{aligned} |x_e x_X| &= 4\pi \frac{v^2}{\lambda^2} |\tilde{\alpha}_{AeX}| \\ &= \frac{3\pi}{2} \alpha_0''(eX) \frac{v^2}{(\alpha m_e)^2} \\ &= 2.0 \times 10^{16} \alpha_0''(eX), \end{aligned} \quad (11)$$

where the limits on $\alpha_0''(eX)$ are presented in Table I. For the most strong constraint that reads

$$|x_e x_\mu| \leq 15.6.$$

For the accepted axion model the existing limitations are several orders of magnitude stronger than our constraints (see, e.g. [6]). However, the results strongly depend on a model applied. Our constraint, being model independent, is complementary to limitations obtained by other methods.

Acknowledgments

This work was supported in part by DFG (grant GZ: HA 1457/7-1) and RFBR ((under grant # 11-02-91343)), Australian research Council. The authors are grateful to Yury Gnedin, Pierre Fayet and Maxim Pospelov for useful and stimulating discussions. The warm hospitality of ECT*, where the work was started, is gratefully acknowledged. SGK is also grateful to UNSW for their hospitality and Gordon Godfrey foundation for their fellowship.

-
- [1] S. Weinberg, Phys. Rev. Lett. **37**, 657 (1976).
 - [2] R.D. Peccei and H.R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).
 - [3] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).
 - [4] F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).
 - [5] J. E. Moody and F. Wilczek, Phys. Rev. D **30**, 130 (1984).
 - [6] K. Nakamura et al (Particle Data Group) JPG **37**, 075021 (2010).
 - [7] S. G. Karshenboim, Phys. Rev. Lett. **104**, 220406 (2010).
 - [8] S. G. Karshenboim, Phys. Rev. D **82**, 113013 (2010).
 - [9] S. G. Karshenboim, Phys. Rev. A **83**, 062119 (2011).
 - [10] P. Fayet, private communication.
 - [11] W. Liu, M. G. Boshier, S. Dhawan, O. van Dyck, P. Egan, X. Fei, M. G. Perdekamp, V. W. Hughes, M. Janousch, K. Jungmann, D. Kawall, F. G. Mariam, C. Pillai, R. Prigl, G. zu Putlitz, I. Reinhard, W. Schwarz, P. A. Thompson, and K. A. Woodle, Phys. Rev. Lett. **82**, 711 (1999).
 - [12] S. G. Karshenboim, Phys. Rep. **422**, 1 (2005).
 - [13] P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys. **80**, 633 (2008).